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## Stepwise Investment and Capacity Sizing under Uncertainty

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**Abstract** The relationship between uncertainty and managerial flexibility is particularly crucial in addressing capital projects. We consider a firm that can invest in a project in either a single (lumpy investment) or multiple stages (stepwise investment) under price uncertainty and has discretion over not only the time of investment but also the size of the project. We confirm that, if the capacity of a project is fixed and the investment premium associated with stepwise investment is positive, then lumpy investment becomes more valuable than a stepwise investment strategy under high price uncertainty. By contrast, if a firm has discretion over capacity, then we show that the stepwise investment strategy always dominates that of lumpy investment. In addition, we show that the total amount of installed capacity under a stepwise investment strategy is always greater than that under lumpy investment.

**Keywords** investment analysis · capacity sizing · flexibility · real options

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## 1 Introduction

In irreversible investment, firms tend to split the projects in distinct phases. We explain this behaviour in a setup where there is uncertainty, discretion over timing, and over the choice of project scale. According to standard economic literature (Arrow and Fisher [5]; Henry [21]), investment decisions are influenced by three main factors, namely, uncertainty, irreversibility, and flexibility. The first refers to the uncertainty in the cash flows that a project generates, the second to the inability to recover the investment cost after investment has taken place, and the third to the discretion over the timing of investment. The latter allows for uncertainty in underlying parameters to resolve before making an irreversible investment decision. Consequently, the ability to optimise the investment timing raises the expected value of the investment opportunity, which, in turn, implies that investment is delayed relative to the traditional net present value (NPV) approach due to the opportunity cost of killing the timing option. In fact, this hesitation is prolonged as uncertainty increases, since the value of waiting increases. Interestingly, however, not only is the negative relationship between uncertainty and investment subject to model specifications (Lund [27]), but, also, it does not extend analogously to other types of flexibilities. Thus, in spite of the extensive literature that challenges the traditional views of how uncertainty and irreversibility explain investment behaviour (Alvarez and Stenbacka [3]; Abel and Eberly [1]), the interaction between uncertainty and different types of flexibilities has not been thoroughly examined yet. For example, models for sequential capacity expansion seldom present a comparison of lumpy and stepwise investment (Gahungu and Smeers [15]), while the ones that do, either ignore discretion over capacity (Gollier *et al.* [17]) or restrict the conclusions of this comparison to the now-or-never investment case (Pindyck [33]). By developing an analytical framework for investment under uncertainty, we explore how discretion over project scale impacts a firm's incentive to invest in stages.

Indeed, one crucial type of managerial discretion is the flexibility to either invest in an entire project at a single point in time (lumpy investment) or divide it into smaller, modular projects and then invest in each one at distinct points in time (stepwise investment). Within the context of sequential capacity expansion, it has been shown that modularity can have crucial implications for the value of a project. For example, Gollier *et al.* [17] compare a sequence of small nuclear power plants with a single nuclear power plant of large capacity under electricity price uncertainty. Assuming that the capacity of each project is fixed, they find that the option value of modularity may trigger investment in the initial module at a level below the now-or-never NPV. By contrast, Kort *et al.* [24] show how uncertainty reduces the value of modularity. More specifically, they show that, in the absence of an investment premium, the stepwise investment strategy dominates lumpy investment. However, if the modularisation of a project is costly and the size of each module is fixed, then, *“... higher uncertainty makes the single-stage investment more attractive relative to the more flexible stepwise investment strategy”*. This happens because high uncertainty lowers a firm's incentive to make costly switches

between stages, thereby promoting a lumpy investment strategy. A limitation of these models is that they study a particular type of flexibility in isolation, when, in reality, firms can typically combine different types of managerial flexibilities. Consequently, how various types of managerial discretion, e.g., discretion over capacity, option to abandon, etc., interact to affect the value of modularity under increasing uncertainty remains an open question. Indeed, although Kort *et al.* [24] has motivated other research in the area of stepwise investment under price uncertainty that considers also the impact of information change between subsequent investment stages (Adkins and Paxson [2]), considerations regarding the impact of other types of managerial discretion have not been formulated analytically.

We address this disconnect by analysing how the flexibility to choose between a lumpy and a stepwise investment strategy interacts with discretion over capacity under price uncertainty. This situation is relevant to various industries, e.g., renewable energy (RE) power plants. Indeed, in the case of both on- and off-shore wind farms an area can, and often is, developed in stages. Additionally, for capital intensive projects, discretion over capacity is particularly crucial, since the installation of a large project increases a firm's exposure to downside risk in the case of a potential downturn, whereas the installation of a small project limits a firm's upside potential if market conditions suddenly become favourable. Thus, we contribute to the existing literature by developing an analytical framework in order to explore how discretion over capacity interacts with the flexibility to choose between lumpy and stepwise investment under price uncertainty. Additionally, we derive analytical results regarding the impact of uncertainty on the optimal investment threshold, the optimal capacity, and the choice of investment strategy. The analytical tractability of our model facilitates a detailed exploration of how market parameters influence investment and capacity sizing decisions, thus enabling further insights on how different types of managerial discretion interact to affect the choice of investment strategy. Hence, the contribution of this work is that it provides a framework for analysing both the dynamics underlying the interaction between different types of managerial discretion and the implications of this interaction for the optimal investment policy.

We proceed in Section 2 by discussing some related literature and introduce assumptions and notation in Section 3. In Section 4, we formulate the problem and derive analytical expressions for the value of the option to invest, the optimal investment threshold, and the corresponding optimal capacity under lumpy (Section 4.1) and stepwise investment (Section 4.2). In addition, we present analytical results regarding the impact of uncertainty on the choice of investment strategy. We present numerical results in Section 5 and conclude in Section 6.

## 2 Related Work

The seminal work of Majd and Pindyck [30] and Dixit and Pindyck [13] has spawned a substantial literature in the area of sequential investment. The former show how traditional valuation methods understate the value of a project by ignoring the flexibility embedded in the time to build, while the latter develop a sequential investment framework with infinite investment options assuming that the project value depreciates exponentially. Extensions in the same line of work include Pawlina and Kort [32], who implement strategic interactions in capital budgeting under market uncertainty and analyse the optimal replacement timing of a production facility. The value of modularity is emphasised in Malchow-Møller and Thorsen [31], who illustrate how the investment policy resembles the simple NPV rule when investing sequentially in subsequent upgrades of a technology. More specifically, they find that the expected value of subsequent upgrades reduces the value of waiting to invest in the current version, while the investment rule is less sensitive to changes in uncertainty. Taking the perspective of hydro pump-storage plant, Doege *et al.* [14] show how operational flexibility can be used for hedging against adverse movements in a portfolio. Within the context of investment in distributed generation capacity, Siddiqui and Maribu [36] analyse how sequential investment may reduce the exposure of a microgrid to natural gas price volatility, and find that a direct (sequential) investment strategy is more preferable for low (high) levels of volatility. By contrast, Kort *et al.* [24] show that, while the value of lumpy investment is always smaller than that of a stepwise investment strategy when the latter entails no investment premium, if the investment premium is positive, then the lumpy investment strategy may dominate provided that uncertainty is sufficiently high. This happens because, high price uncertainty reduces the incentive to make costly switches between stages. Siddiqui and Takashima [35] combine strategic interactions with sequential capacity expansion in order to explore how sequential decision making offsets the effect of competition. They find that the loss in the value of a firm due to competition is reduced when the firm invests in stages and specify the conditions under which sequential capacity expansion is more valuable for a duopolist firm than for a monopolist.

From a more empirical standpoint, Rodrigues and Armada [34] present a real options approach to the valuation of modular projects, and show that modularisation can increase the value of a project depending on the relative values, costs, and risk of each modular configuration. Gamba and Fusari [16] develop a real options valuation approach in order to address the issues that a modularisation process poses in terms of financial valuation for capital budgeting. They first create a stochastic optimal control framework for the six modular operators proposed by Baldwin and Clark [7] and then adopt the least-squares Monte Carlo method of Longstaff and Schwartz [26] in order to cope with the dynamic programming feature of the valuation problems. While the aforementioned literature offers a thorough analytical and empirical treatment of the value of modularity and sequential investment under uncertainty, it ignores the potential implications

of allowing for other types of managerial discretion that firms typically consider when designing an optimal investment policy, e.g., discretion over capacity, suspension and resumption options, etc.

Indeed, apart from discretion over the investment strategy, e.g., lumpy versus stepwise, firms typically also have discretion over the size of a project, in the form of installed capacity. Dangl [12] addresses the problem of a firm that invests in a project with continuously scalable capacity under demand uncertainty, and shows that, even when demand is high, low uncertainty makes waiting for further information the optimal strategy. A similar approach is adopted by Bøckman *et al.* [9] for valuing small hydropower projects under electricity price uncertainty, however, unlike Dangl [12], they assume a cost function that is convex in capacity, and, therefore, their model is more pertinent to the energy sector. Huisman and Kort [22] introduce game-theoretic considerations and show how, in a duopolistic competition, a leader can use discretion over capacity strategically in order to deter a follower's entry temporarily. A policy-oriented model for investment and capacity sizing is presented by Boomsma *et al.* [8], who analyse the impact of uncertainty stemming from different types of policy mechanisms on investment and capacity sizing decisions. The impact of risk aversion on such decisions when a firm has operational flexibility is addressed in Chronopoulos *et al.* [11], who find that higher risk aversion facilitates investment by decreasing the optimal capacity of a project. Although discretion over capacity has crucial implications for investment and operational decisions, analytical models that study the implications of this flexibility within the context of lumpy versus stepwise capacity expansion are limited.

Apart from analysing the value of discretion over capacity in isolation, a strand of literature combines it with various types of operational flexibilities. For example, He and Pindyck [20] allow for demand uncertainty and examine the technology and capacity choice problem of a firm that can install either output-specific or flexible capital, which may be used to produce different outputs. They formulate the capacity choice problem as a stochastic control problem, and show that the value of the firm equals the value of its installed capital plus the expected value of its options to add capacity in the future. Considering the choice between two types of technologies, Takashima *et al.* [37] find that price uncertainty induces investors to maximise expected profits by building larger plants, while the consideration of mutually exclusive projects increases the option value of the entire investment opportunity. Hagspiel *et al.* [19] compare a flexible scenario, in which a firm can adjust production over time with the capacity level as the upper bound, to the inflexible scenario, in which a firm fixes production at capacity level from the moment of investment onward. Among other results, they find that the flexible firm invests in higher capacity than the inflexible firm and that the capacity difference increases with uncertainty.

We extend the existing literature by developing an analytical framework that combines two important types of managerial discretion, i.e., the flexibility to invest in either a single or multiple stages with discretion over capacity. Although increasing uncertainty favours a lumpy over a more flexible, yet more costly, stepwise

investment strategy when the capacity of a project is fixed, the implications from allowing for discretion over capacity are not thoroughly examined yet. For this reason, we assume that the capacity of the project is continuously scalable, and, in line with Dangl [12], the firm has the option to fix the capacity of the project at investment. We first confirm the results of Kort *et al.* [24] and then show that, although the relative value of the two strategies decreases with greater uncertainty, the stepwise investment strategy always dominates that of lumpy investment. This seemingly counter-intuitive result happens because the firm can optimise the size of the project in response to an increase in the cost of the stepwise investment strategy relative to that of lumpy investment. Intuitively, the extra flexibility to optimise the size of the project mitigates the loss in project value due to the higher cost associated with the flexibility to proceed in stages, thereby offsetting the benefit of a lower investment cost via lumpy investment.

### 3 Assumptions and Notation

We consider a price-taking firm that holds an option to invest in a project of infinite lifetime that may be completed in either a single or a sequence of  $i < \infty$  discrete stages with  $i \in \mathbb{N}$ . Also, the firm can either exercise an investment option immediately or delay investment in the light of price uncertainty. We assume that there is no variable production cost and that the output price at time  $t$ ,  $P_t$ , where  $t \geq 0$  is continuous and denotes time, follows a geometric Brownian motion (GBM) that is described in (1)

$$dP_t = \mu P_t dt + \sigma P_t dZ_t, P_0 \equiv P > 0 \quad (1)$$

where  $\mu$  is the annual growth rate,  $\sigma$  is the annual volatility, and  $dZ_t$  is the increment of the standard Brownian motion. Also,  $\rho > \mu$  is the subjective discount rate. The capacity of the project is denoted by  $K_j$  when the firm has discretion over investment timing and by  $\bar{K}_j$  when the firm invests immediately, thus exercising a now-or-never investment opportunity. Additionally,  $\bar{F}_j(\cdot)$  is the expected value of the now-or-never investment opportunity, where  $j \in \{\ell, s_i\}$  (denoting lumpy and staged investment respectively), while  $\bar{K}_j^*$  is the corresponding optimal capacity. For example,  $\bar{F}_\ell(\cdot)$  denotes the expected value of the now-or-never investment opportunity under lumpy investment and  $\bar{K}_\ell^*$  is the corresponding optimal capacity. If the option to defer investment is available, then  $F_j(\cdot)$  denotes the maximised value of the option to invest in stage  $j$  exclusive of subsequent stages, while  $\tau_j$ ,  $P_j^*$ , and  $K_j^*$  denote the time of investment, the optimal investment threshold, and the corresponding optimal capacity, respectively. The investment cost,  $I(K_j)$ , is indicated in (2)

$$I(K_j) = a_j K_j + b K_j^\gamma, a_j, b, \text{ and } \gamma > 1 \quad (2)$$

where  $\gamma > 1$  implies that this model is more suitable for describing projects that exhibit diseconomies of scale. In the energy sector, this is the case with RE power plants, while more general examples where the use of a convex cost function can be realistic include a monopsonistic environment in which a firm contemplates investment facing increasing prices due to increasing demand. As it becomes clear in Section 4, the assumption  $\gamma > 1$  should be considered as an implication of the model itself, and, therefore, is not restricting the analytical results. For the purpose of comparing a lumpy investment to a strategy that entails a series of modular investments, we assume that each individual stage of the stepwise investment strategy is less costly than the entire project. However, in line with Kort *et al.* [24], we assume that the flexibility to proceed in stages is costly, and, thus, requires the firm to incur a premium. Thus, the total investment cost under a stepwise investment strategy is greater than that under lumpy investment, as indicated in (3).

$$I(K_{s_i}^*) < I(K_\ell^*), \forall i \in \mathbb{N} \quad \text{and} \quad \sum_i I(K_{s_i}^*) > I(K_\ell^*) \quad (3)$$

This assumption is required in order to distinguish a lumpy from a modular project based on their cost, since the capacity of the project is scalable. Although condition (3) may hold for an arbitrary capacity level, we express it in terms of the optimal capacity,  $K_j^*$ , and not the state variable,  $K_j$ . This enables a direct association with the investment cost parameters and facilitates a better intuition of the endogenous nature of the optimal capacity. Note that condition (3) is equivalent to  $a_{s_i} < a_\ell, \forall i \in \mathbb{N}$  and  $\sum_i a_{s_i} > a_\ell$ .

In order to compare our results to Kort *et al.* (2010), we also consider the benchmark case in which the capacity of the project is fixed and such that  $K_{s_1} + K_{s_2} = K_\ell$ , while the investment cost satisfies the condition  $I_\ell < I_{s_1} + I_{s_2}$ . This implies that, under stepwise investment, the sum of the capacities of the modular projects equals that of the lumpy project, yet, due to the investment premium, the investment cost of the stepwise investment strategy is greater than that of the lumpy investment. Note that in the case of Kort *et al.* [24] the capacities are set exogenously, and, therefore, it is possible to replicate the single stage investment by setting the capacity of first stage equal to that of the lumpy investment. This is not possible if a firm has discretion over project scale, because the optimal capacity is determined endogenously and depends on the optimal investment threshold, which, in turn, depends on the investment cost by assumption 3. The latter, is different for lumpy and stepwise investment. Finally, note that, although a firm may have the flexibility to respond to low prices by producing at a level below the installed capacity, in this paper, we assume that a firm does not have production flexibility. This is often referred to as the *clearance* assumption and is widely used in the literature (Chod and Rudi [10]; Anand and Girotra [4]). For example, in the energy sector this assumption is relevant to baseload and RE power plants. Additionally, fixed costs, e.g., commitments to suppliers and production ramp-up, make it too costly to produce below the capacity level



(Goyal and Netessine [18]). In the car industry, firms often prefer to reduce prices in order to maintain production at full capacity, instead of producing below capacity (Mackintosh [29]).

#### 4 Model

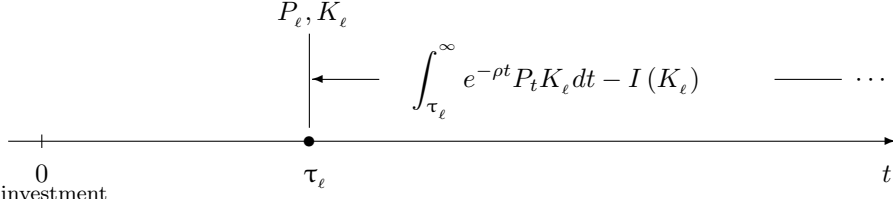
The firm's optimisation objective under each investment strategy, i.e., lumpy and stepwise investment, is summarised in (4). The outer maximisation corresponds to the general decision on whether to invest immediately or delay investment. If the firm decides to wait for an infinitesimal time interval  $dt$ , then, according to the Bellman principle, the value that the firm holds is the discounted expected value of the capital appreciation of the option to invest. This is represented by the first argument of the maximisation on the right-hand side of (4). By contrast, the second argument of the outer maximisation represents the value that the firm receives if it decides to exercise a now-or-never investment opportunity. More specifically, the inner maximisation indicates that when the firm decides to invest it will choose the capacity of the project in such a way that maximises its expected NPV.

$$F_j(P) = \max \left\{ (1 - \rho dt) \mathbb{E}_P [F_j(P + dP)], \max_{\bar{K}_j} [\bar{F}_j(P, \bar{K}_j)] \right\}, j = \ell, s_i \text{ and } i = 1, 2 \quad (4)$$

Initially, we assume that investment takes place immediately, i.e., at  $P_0 \equiv P$ . This implies that the output price at investment is known and enables the calculation of the corresponding optimal capacity by maximizing the value of the now-or-never investment opportunity. In turn, this yields the expression relating the initial output price to the corresponding optimal capacity, i.e.,  $\bar{K}_\ell^*(P)$ . We then allow for the option to defer investment and maximize the value of the investment opportunity by determining the optimal investment threshold taking into account the inner extremum of optimal capacity choice at investment. The solution to this optimization problem is obtained by equating the marginal benefit of delaying investment, MB, to the marginal cost, MC. Thus, we obtain the expression relating the optimal investment threshold to the optimal capacity, i.e.,  $P_\ell^* \equiv P_\ell(K_\ell^*)$ . Inserting this expression into the condition of optimal capacity choice at  $\tau_\ell$ , we obtain the optimal capacity of the project, i.e.,  $K_\ell^* \equiv K_\ell(P_\ell^*)$ . Finally, using  $K_\ell^*$ , we can determine the corresponding optimal investment threshold price  $P_\ell^*$ .

##### 4.1 Lumpy Investment

We begin by assuming that the firm adopts a lumpy investment strategy. Following the approach of Chronopoulos *et al.* [11], the firm can delay investment until  $\tau_\ell$ , at which point it must fix the capacity of the entire project,  $K_\ell$ , and incur the investment cost,  $I(K_\ell)$ , thereby receiving a perpetual stream of stochastic cash flows, as shown in Figure 1. Consequently,  $K_\ell$  is a function of the output price,  $P_\ell$ , at time  $\tau_\ell$ .



**Fig. 1** Lumpy investment

We first address the inner maximisation in (4). Hence, we assume that the firm ignores the option to wait for more information and invests in the project immediately. The expected value of the now-or-never investment opportunity is indicated in (5).

$$\bar{F}_\ell(P, \bar{K}_\ell) = \frac{P\bar{K}_\ell}{\rho - \mu} - I(\bar{K}_\ell) \quad (5)$$

Consequently, at investment, the output price,  $P$ , is known, and, therefore, the firm needs to determine only the corresponding optimal capacity,  $\bar{K}_\ell^*$ , by maximising the value of the now-or-never investment opportunity, as indicated in (6).

$$\max_{\bar{K}_\ell} \bar{F}_\ell(P, \bar{K}_\ell) \Rightarrow \bar{K}_\ell^*(P) = \left[ \frac{1}{b\gamma} \left( \frac{P}{\rho - \mu} - a_\ell \right) \right]^{\frac{1}{\gamma-1}} \quad (6)$$

We proceed by considering the outer maximisation in (4). If the firm can defer investment, then the value of the option to invest is described in (7), where  $\mathcal{S}$  denotes the set of stopping times of the filtration generated by the price process and  $\mathbb{E}_P$  is the expectation operator, which is conditional on the initial value,  $P$ , of the price process.

$$F_\ell(P) = \sup_{\tau_\ell \in \mathcal{S}} \mathbb{E}_P \left[ \int_{\tau_\ell}^{\infty} e^{-\rho t} P_t K_\ell^* dt - I(K_\ell^*) \right] \quad (7)$$

Using the law of iterated expectations and the strong Markov property of the GBM, which states that price values after time  $\tau_\ell$  are independent of the values before  $\tau_\ell$  and depend only on the value of the process at  $\tau_\ell$ , we can rewrite (7) as in (8). The stochastic discount factor  $\mathbb{E}_P[e^{-\rho\tau_\ell}] = \left(\frac{P}{P_\ell}\right)^\beta$  (Dixit and Pindyck [13], p.315), where  $\beta > 1$  is the positive root of  $\frac{1}{2}\sigma^2 x(x-1) + \mu x - \rho = 0$ . Notice that, at investment, the optimal capacity,  $K_\ell^*$ , is related to the optimal investment threshold via (6), i.e.,  $K_\ell^* \equiv K_\ell(P_\ell^*)$ . Thus, the now-or-never NPV rule serves as an intermediate step for determining the endogenous relationship between the optimal capacity of the project and the optimal investment threshold.

$$F_\ell(P) = \sup_{\tau_\ell \in \mathcal{S}} \mathbb{E}_P[e^{-\rho\tau_\ell}] \mathbb{E}_{P_\ell} \left[ \int_0^\infty e^{-\rho t} P_t K_\ell^* dt - I(K_\ell^*) \right] = \max_{P_\ell \geq P} \left( \frac{P}{P_\ell} \right)^\beta \left[ \frac{P_\ell K_\ell^*}{\rho - \mu} - I(K_\ell^*) \right] \quad (8)$$

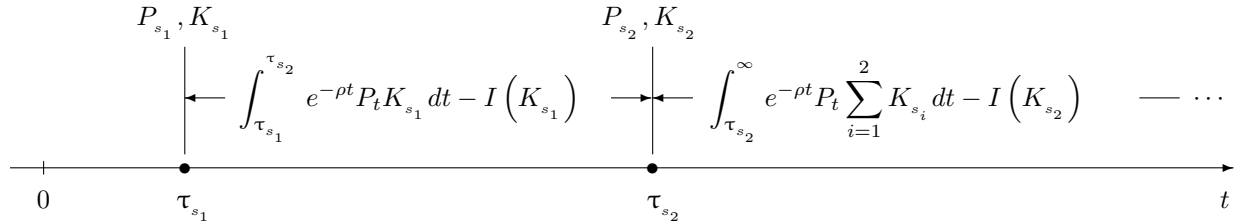
$$\text{where } K_\ell^* \equiv K_\ell(P_\ell^*) = \left[ \frac{1}{b\gamma} \left( \frac{P_\ell^*(K_\ell^*)}{\rho - \mu} - a_\ell \right) \right]^{\frac{1}{\gamma-1}}$$

Solving the unconstrained maximisation problem (8), we can express the maximised option value,  $F_\ell(P)$ , as in (9). The endogenous constant,  $A_\ell$ , the optimal investment threshold,  $P_\ell^*$ , and the corresponding optimal capacity,  $K_\ell^*$ , can be determined equivalently via value-matching and smooth-pasting conditions between the two branches of (9) together with the condition for optimal capacity choice at investment (6) and are indicated in (A-7), (A-8), and (A-9), respectively for  $j = \ell$  (all proofs can be found in the appendix).

$$F_\ell(P) = \begin{cases} A_\ell P^\beta & , \text{ for } P < P_\ell^* \\ \frac{PK_\ell^*}{\rho - \mu} - I(K_\ell^*) & , \text{ for } P \geq P_\ell^* \end{cases} \quad (9)$$

#### 4.2 Stepwise Investment

Next, we assume that the firm adopts a stepwise investment strategy, that comprises of two stages, i.e.,  $i \leq 2$ . While it is possible that  $i > 2$ , the number of stages should, nevertheless, be finite in order to ensure that the size of the entire project does not diverge. As indicated in Figure 2, the firm has the option to delay investment in the first stage until  $\tau_{s_1}$ , at which point it must fix the corresponding capacity,  $K_{s_1}$ , and incur the investment cost,  $I(K_{s_1})$ . The firm receives the revenues of the first stage until  $\tau_{s_2}$ , at which point it fixes the capacity of the second stage,  $K_{s_2}$  and incurs the investment cost  $I(K_{s_2})$ . After the firm invests in the second stage, it receives the revenues from both stages.



**Fig. 2** Stepwise investment

The optimal capacity at each stage of the project when the firm invests immediately is obtained by maximising the value of the now-or-never investment opportunity. Following the same approach as in the case of lumpy investment, the optimal capacity for each stage is indicated in (10).

$$\max_{\bar{K}_{s_i}} \bar{F}_{s_i}(P, \bar{K}_{s_i}) \Rightarrow \bar{K}_{s_i}^*(P) = \left[ \frac{1}{b\gamma} \left( \frac{P}{\rho - \mu} - a_{s_i} \right) \right]^{\frac{1}{\gamma-1}} \quad (10)$$

Notice that the value of the now-or-never investment opportunity is the sum of the maximised NPVs from each stage, i.e.,  $\bar{F}_s(P) = \sum_i \bar{F}_{s_i}(P, \bar{K}_{s_i}^*)$ .

If the option to delay investment is available, then the optimisation objective is described in (11)

$$F_s(P) = \sup_{\tau_{s_1} \in \mathcal{S}} \mathbb{E}_P \left[ \sup_{\tau_{s_2} \geq \tau_{s_1}} \mathbb{E}_P \left[ \int_{\tau_{s_1}}^{\tau_{s_2}} e^{-\rho t} P_t K_{s_1}^* dt - I(K_{s_1}^*) + \int_{\tau_{s_2}}^{\infty} e^{-\rho t} P_t \sum_{i=1}^2 K_{s_i}^* dt - I(K_{s_2}^*) \right] \right] \quad (11)$$

where  $K_{s_i}^* \equiv K_{s_i}(P^*)$ ,  $i = 1, 2$ . Notice that by completing the first stage, the firm receives the option to proceed to the second. As a result, the option to invest in the first stage may be seen as a compound option. In fact, since the cash flows accrue over disjoint time intervals the value of the option to invest is separable.

By decomposing the first integral on the right-hand side of (11), we can express the original problem as two separate optimal stopping-time problems, as in (12)

$$F_s(P) = \sup_{\tau_{s_1} \in \mathcal{S}} \mathbb{E}_P \left[ \int_{\tau_{s_1}}^{\infty} e^{-\rho t} P_t K_{s_1}^* dt - I(K_{s_1}^*) \right] + \sup_{\tau_{s_2} \geq \tau_{s_1}} \mathbb{E}_P \left[ \int_{\tau_{s_2}}^{\infty} e^{-\rho t} P_t K_{s_2}^* dt - I(K_{s_2}^*) \right] \quad (12)$$

and, following the same steps as in (8), we obtain (13).

$$F_s(P) = \max_{P_{s_1} \geq P} \left( \frac{P}{P_{s_1}} \right)^{\beta_1} \mathbb{E}_{P_{s_1}} \left[ \int_0^{\infty} e^{-\rho t} P_t K_{s_1}^* dt - I(K_{s_1}^*) \right] + \max_{P_{s_2} \geq P_{s_1}} \left( \frac{P}{P_{s_2}} \right)^{\beta_1} \mathbb{E}_{P_{s_2}} \left[ \int_0^{\infty} e^{-\rho t} P_t K_{s_2}^* dt - I(K_{s_2}^*) \right] \quad (13)$$

Notice that, like in (8),  $K_{s_i}^* \equiv K_{s_i}(P_{s_i}^*) = \left[ \frac{1}{b\gamma} \left( \frac{P_{s_i}^*(K_{s_i}^*)}{\rho - \mu} - a_{s_i} \right) \right]^{\frac{1}{\gamma-1}}$ .

The solution of each of the two optimal stopping-time problems on the right-hand side of (13) is expressed in (14), where  $A_{s_i}$ ,  $P_{s_i}^*$ , and  $K_{s_i}^*$  are indicated in (A-7), (A-8), and (A-9), respectively. Notice that the value of the option to invest is the sum of the respective option values of each stage, i.e.,  $F_s(P) = \sum_i F_{s_i}(P)$ .

$$F_{s_i}(P) = \begin{cases} A_{s_i} P^{\beta} & , \text{ for } P < P_{s_i}^* \\ \frac{PK_{s_i}^*}{\rho - \mu} - I(K_{s_i}^*) & , \text{ for } P \geq P_{s_i}^* \end{cases} \quad (14)$$

**Proposition 1** *The optimal investment threshold and the corresponding optimal capacity under lumpy and stepwise investment are:*

$$P_j^*(K_j^*) = \frac{I(K_j^*)}{K_j^*} \frac{\beta(\rho - \mu)}{\beta - 1} \quad \text{and} \quad K_j^* = \left[ \frac{a_j}{b} \frac{1}{\gamma(\beta - 1) - \beta} \right]^{\frac{1}{\gamma-1}}, \quad \gamma(\beta - 1) - \beta > 0 \quad (15)$$

Assuming that  $\tau_{s_1} < \tau_{s_2}$ , Proposition 2 indicates that the decision to invest in the first stage is independent of the presence of the second. Notice first that the structure of the cost function in (2) and Proposition 1 imply that  $P_{s_1}^* < P_{s_2}^*$  if  $a_{s_1} < a_{s_2}$ . In turn, the latter condition implies that the two investments within a stepwise investment strategy are not undertaken at the same time. Consequently, the assumption  $\tau_{s_1} < \tau_{s_2}$  is satisfied. Intuitively, Proposition 2 is a consequence of the optimality of myopic behaviour based on which a firm disregards subsequent investment decisions when evaluating the current one. Within the context of capacity expansion, this property implies that an investment in new capacity is evaluated assuming that it is the last one in the horizon. The optimality of myopic behaviour is not generally true but holds in the benchmark cases of monopoly (Pindyck [33]) and perfect competition (Leahy [25]; Baldursson and Karatzas [6]). Optimality of myopia also holds within a context of strategic interactions provided that the profit is additively separable if more than one technology is considered (Baldursson and Karatzas [6]).

**Proposition 2**  $P_{s_1}^*$  is independent of  $P_{s_2}^*$ .

In line with the standard real options intuition, Proposition 3 indicates that greater uncertainty raises both the optimal capacity of the project and the optimal investment threshold. This happens because greater uncertainty increases the opportunity cost of an irreversible investment decision, thereby raising the value of waiting. Furthermore, from (6) we know that the optimal capacity of the project is a monotonic function of the output price. Consequently, an increase in the optimal investment threshold results in the installation of a bigger project.

**Proposition 3**  $\frac{\partial K_j^*}{\partial \sigma} > 0$  and  $\frac{\partial P_j^*}{\partial \sigma} > 0$ .

#### 4.3 Lumpy versus Stepwise Investment

In this section, we analyse the implications of discretion over capacity for the optimal investment strategy. Interestingly, as Proposition 4 indicates, if the firm has discretion over capacity, then the value of the option to proceed in stages is always greater than that under lumpy investment. This is in contrast to Kort *et al.* [24] who show that, under relatively large uncertainty, the single stage investment is more attractive relative to a more flexible, yet more costly, stepwise investment strategy. This seemingly counter-intuitive result is based on the endogenous relationship between the price at investment and the capacity of the project. Notice that, if a firm has discretion over capacity, then, according to (15), the optimal capacity,  $K_j^*$ , is non-negative if  $\gamma(\beta - 1) - \beta > 0$ . However, while greater uncertainty lowers the relative value of the two strategies, it also decreases  $\beta$ . According to Proposition 4, the relative value of the two strategies does not decrease below one for non-negative values of  $K_j^*$ . Intuitively, although the value of the stepwise investment strategy is reduced due to the cost that a firm incurs for the flexibility to proceed in stages, the extra flexibility to scale the capacity of the project allows the firm to offset the reduction in the value of the stepwise investment strategy

completely. Indeed, if the capacity of the project was fixed, then greater uncertainty would delay investment but the amount of installed capacity would remain unaffected. By contrast, discretion over capacity allows a firm to respond to an increase in the investment cost by optimising the endogenous relationship between the size of the project and the time of investment. Hence, contrary to Kort *et al.* [24], there exists no investment premium for which the firm is indifferent between the two strategies. This would only happen if the cost of any given module was equal to that of the lumpy project. However, this would violate assumption (3) since then there would be no distinction between the lumpy and the modular project.

**Proposition 4** *If a firm has discretion over capacity, then  $F_s(P) > F_\ell(P)$ .*

From (15) we see that the existence of an optimal solution to the investment problem under each strategy requires that the cost function is strictly convex, i.e.,  $\gamma(\beta - 1) - \beta > 0 \Leftrightarrow \gamma > \frac{\beta}{\beta-1} > 1$ . Therefore, the convexity of the cost function is not an assumption, as indicated in (2), but rather a property implied by the analytical framework itself. More specifically, convexity ensures that the optimal stopping-time problem is finite, since, otherwise, it is always optimal to delay investment. Indeed, if  $\gamma > \frac{\beta}{\beta-1}$ , then  $0 < K_j^* < \infty$ , whereas if  $\gamma \rightarrow \frac{\beta}{\beta-1}$ , then  $K_j^* \rightarrow \infty$ . Consequently, the result of Proposition 4 is in line with the more general intuition that a firm is typically induced to adjust its capital stock more slowly due to diseconomies of scale associated with rapid changes in the investment cost. Hence, a convex investment cost implies that it is more expensive to perform adjustments, e.g., expand capacity, at a greater than at a lower rate (Jørgensen and Kort [23]). Additionally, note that  $\gamma > \frac{\beta}{\beta-1}$  is a consequence of the exogenous price, while the result of Proposition 4 depends upon the endogenous relationship between the price at investment and the capacity of the project, as this is described in (6). Allowing for the price to depend on the amount of quantity produced via an inverse demand function will result in a concave cost function (Dangl [12]), yet the qualitative (positive) relationship between the price and capacity will remain the same. Indeed, Dangl [12] illustrates how the optimal capacity increases monotonically with the output price under economies of scale, i.e.,  $\gamma < 1$ . Since the endogenous relationship between the price at investment and the capacity of the project remains unaffected, the qualitative result of Proposition 4 should hold under both diseconomies and economies of scale. Nevertheless, the rigorous derivation of this result for  $\gamma < 1$  is left for future work.

Another consequence of the endogenous relationship between the output price at investment and the size of the project, is that, if condition (3) holds, then the amount of installed capacity under lumpy investment is lower than the total amount of capacity installed under a stepwise investment strategy, as shown in Proposition 5. Indeed, as the investment cost associated with the stepwise investment strategy increases, it raises both the optimal investment threshold and the amount of installed capacity. Consequently, the firm compensates for the extra cost it incurs for the flexibility to proceed in stages by adjusting the size of the project so that it offsets the reduction in the value of the investment opportunity. As a result, the stepwise investment strategy leads to the installation of a bigger project than that under lumpy investment. This is in

contrast to Kort *et al.* [24], where a firm may delay investment due to an increase in the investment cost, yet it can install a fixed amount of capacity. Notice also that, if assumption (3) is extended to reflect a project with more than two stages, then intuition suggests that the result of Proposition 5 can be extended to allow for an arbitrary number of stages.

**Proposition 5**  $K_\ell^* < \sum_{i=1}^n K_{s_i}^* \Leftrightarrow a_\ell^{\frac{1}{\gamma-1}} < \sum_{i=1}^n a_{s_i}^{\frac{1}{\gamma-1}}.$

In order to obtain a deeper intuition of Proposition 4 and the underlying dynamics that determine the optimal investment policy, we analyse the impact of uncertainty on the marginal benefit (MB) and the marginal cost (MC) of delaying investment under each investment strategy assuming that the capacity of the project is either fixed or scalable. Therefore, we first express the firm's maximised option value as in (16)

$$F_j(P) = \max_{P_j \geq P} \left( \frac{P}{P_j} \right)^\beta \left[ \frac{P_j K_j}{\rho - \mu} - I(K_j) \right] \quad (16)$$

and then describe the first-order necessary condition for the optimisation problem (16) by equating the MB of delaying investment to the MC, as in (17).

$$\frac{\beta I(K_j^*)}{P_j^*} + \frac{K_j^*}{\rho - \mu} = \frac{\beta K_j^*}{\rho - \mu} \quad (17)$$

The first term on the left-hand side of (17) is positive and represents the incremental project value created by a marginal increase in the output price. Notice that this term is a decreasing function of the output price, since waiting longer enables the project to start at a higher initial price, yet the rate at which this benefit accrues diminishes due to the effect of discounting. The second term is also positive and represents the reduction in the MC of waiting to invest due to saved investment cost. Together, these two terms constitute the MB of delaying investment. The right-hand side of (17) represents the MC of delaying investment. This term is positive and reflects the opportunity cost of forgone cash flows. As shown in Corollary 1, when the output price is low it is worthwhile to postpone investment since the MB is greater than the MC.

**Corollary 1** *The MB is steeper than the MC.*

As Proposition 6 indicates, if the capacity of the project is fixed, then greater uncertainty decreases both the MB and the MC of delaying investment, however, the impact of uncertainty on the MC is more pronounced than that on the MB. By contrast, the opposite is true if the firm has discretion over capacity. In fact, although in both cases greater uncertainty postpones investment, the incentive to delay investment is greater when the firm has the flexibility to scale the capacity of the project.

**Proposition 6** *If  $K_j$  is fixed, then  $\frac{\partial}{\partial \sigma} MB < 0$ ,  $\frac{\partial}{\partial \sigma} MC < 0$ , and  $|\frac{\partial}{\partial \sigma} MB| < |\frac{\partial}{\partial \sigma} MC|$ , whereas if  $K_j$  is scalable, then  $\frac{\partial}{\partial \sigma} MB > 0$ ,  $\frac{\partial}{\partial \sigma} MC > 0$ , and  $\frac{\partial}{\partial \sigma} MB > \frac{\partial}{\partial \sigma} MC$ .*

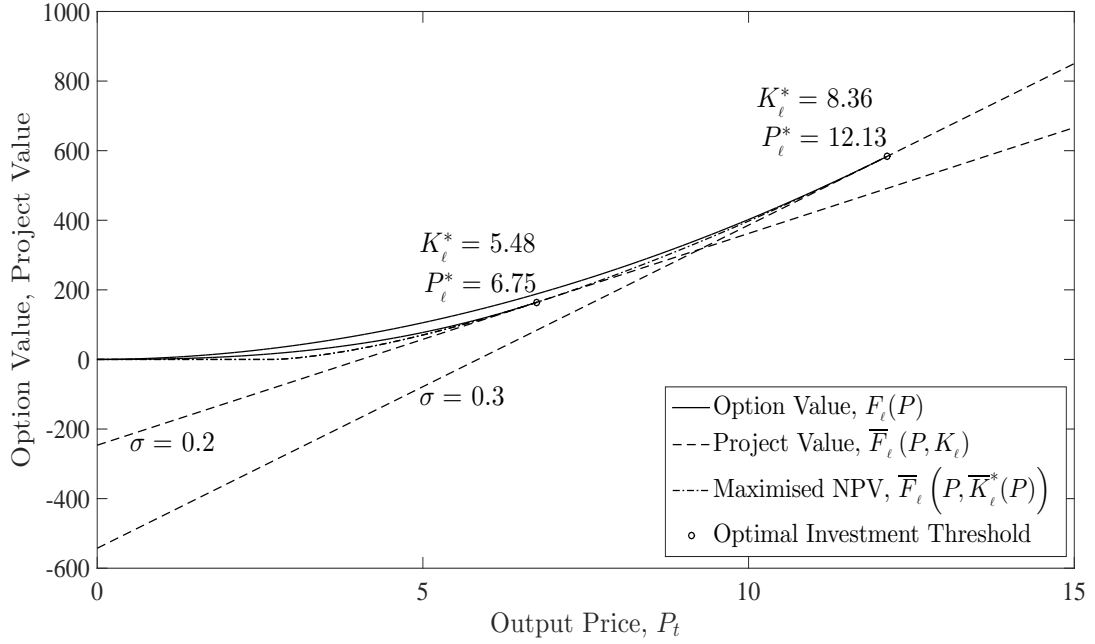
Indeed, if the capacity of the project is fixed, i.e.,  $K_j^* \equiv K_j$ , then from (17) we see that both the MB and MC of delaying investment decrease with greater uncertainty, since  $\frac{\partial \beta}{\partial \sigma} < 0$ . In addition, from (A-13) we have  $\frac{I(K_j)}{P_j^*} < \frac{K_j}{\rho - \mu}$ , and, therefore, greater uncertainty lowers the MC by more than the MB. As a result, the marginal value of delaying investment increases, thereby raising the incentive to postpone investment. Intuitively, although the extra benefit from allowing the project to start at a higher output price is fixed, the extra benefit from saving on the investment cost and the extra cost of the forgone cash flows decrease due to the effect of discounting. In fact, the latter becomes more pronounced as both the output price and the volatility increase. By contrast, if the capacity of the project is scalable, then the increase in the optimal capacity of the project with greater uncertainty presents an opposing force, which mitigates the reduction in the value of  $\beta$ . As Proposition 6 indicates, in the latter case both the MB and MC of delaying investment increase with greater uncertainty, and, unlike the case of fixed capacity, the MB increases by more than the MC, thus increasing the incentive to delay investment. Consequently, discretion over capacity allows the firm to manage price uncertainty more efficiently by adjusting the size of the project in response to an increase in the investment cost.

## 5 Numerical Examples

For the numerical examples we assume that  $\mu = 0.01$ ,  $\rho = 0.1$ , and  $\sigma \in [0, 0.4]$ . Also, the cost parameters are  $a_\ell = 30$ ,  $a_{s_1} = 15$ ,  $a_{s_2} = 25$ ,  $b = 0.5$ , and  $\gamma = 3$ . In order to compare our results with the case of fixed capacity, we assume that the investment cost in the latter case is  $I_\ell = 1000$ ,  $I_{s_1} = 500$ , 510, 520, and  $I_{s_2} = 900$  for lumpy and stepwise investment respectively, while the corresponding capacity levels are  $K_\ell = 10$ ,  $K_{s_1} = 3.4$ , and  $K_{s_2} = 6.6$ . Notice that if the capacity of the project is not scalable, then, in line with Kort *et al.* [24], stepwise is more costly than lumpy investment, i.e.,  $I_\ell = 1000 < I_{s_1} + I_{s_2}$ , yet  $K_{s_1} + K_{s_2} = 10 = K_\ell$ . Figure 3 illustrates the option and project value as well as the maximised NPV in the case lumpy investment for  $\sigma = 0.2, 0.3$ . Notice that greater price uncertainty increases the opportunity cost of investment and raises the value of the investment opportunity. In turn, this postpones investment and increases both the optimal investment threshold and corresponding optimal capacity.

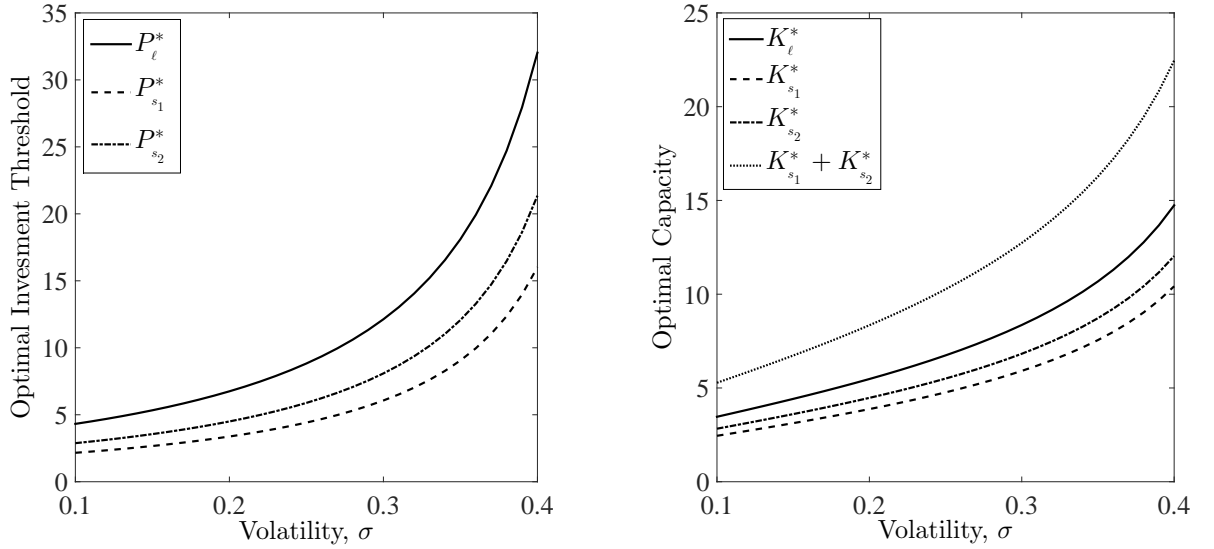
Figure 4 illustrates the impact of uncertainty on the optimal investment threshold under scalable capacity, as well as on the optimal capacity of the project. According to the left panel,  $P_{s_1}^* < P_{s_2}^*$ , and, therefore, the numerical assumptions satisfy the condition  $\frac{I(K_{s_1}^*)}{I(K_{s_2}^*)} < \frac{K_{s_1}^*}{K_{s_2}^*}$ . Additionally, as the right panel illustrates, with the flexibility to scale the size of the project the total capacity when proceeding in stages exceeds that of the lumpy investment, as shown in Proposition 5. In fact, the wedge between  $K_{s_1}^* + K_{s_2}^*$  and  $K_\ell^*$  reflects the extra value that the firm has due its discretion over capacity. Notice that, since  $K_{s_1}^* + K_{s_2}^* > K_\ell^*$  and  $a_{s_1} + a_{s_2} > a_\ell$ , the condition that stepwise investment is more costly than lumpy investment, as indicated in





**Fig. 3** Option value, project value, and maximised NPV under lumpy investment for  $\sigma = 0.2, 0.3$

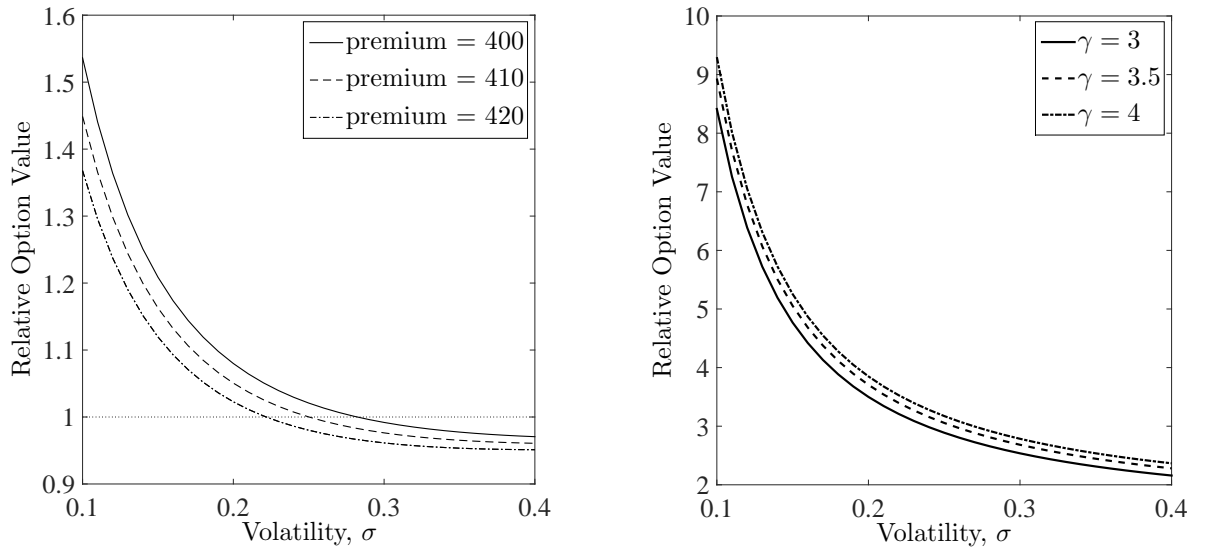
(3), is also satisfied. Consequently, apart from discretion over capacity, the remaining assumptions are the same as the ones underlying the model of Kort *et al.* [24].



**Fig. 4** Optimal investment threshold (left) and optimal capacity (right) versus  $\sigma$

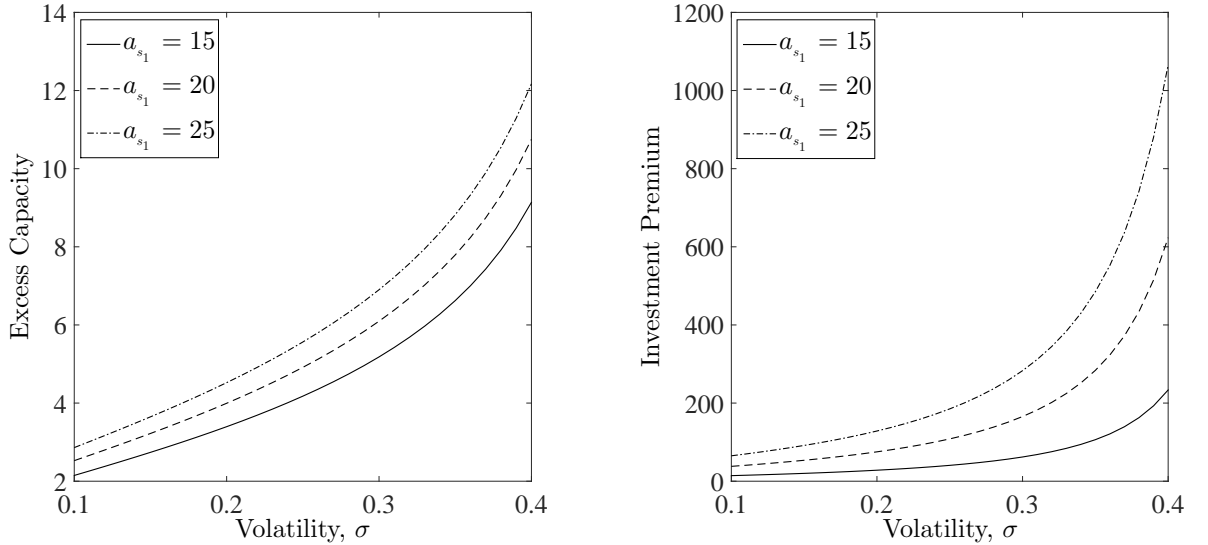
Figure 5 illustrates the impact of uncertainty on the relative value of the two strategies, i.e.,  $\frac{F_s(P)}{F_\ell(P)}$ , under fixed (left panel) and scalable capacity (right panel). The left panel confirms the results of Kort *et al.* [24] for the case in which stepwise investment requires a positive investment premium. Indeed, Kort *et al.* (2010) show that greater price uncertainty lowers the critical level of the investment cost premium for which the lumpy

and stepwise investment strategies are equally good. Equivalently, this implies that a greater investment cost premium lowers the critical level of price uncertainty for which the firm is indifferent between the two strategies. The critical level of price uncertainty for each level of investment cost premium is illustrated in the left panel of Figure 5 and is located at the intersection between the curves and the horizontal line. As the left panel illustrates, there exists a level of uncertainty for which the firm would be indifferent between a lumpy and a stepwise investment strategy. Indeed, if the capacity of the project is fixed, then the relative value of the two strategies is greater than one for low levels of uncertainty, yet drops below one as uncertainty increases (left panel). This result is more pronounced as the investment premium,  $\sum_i I_{s_i} - I_\ell$ , of the stepwise investment strategy increases. Hence, with greater uncertainty, lumpy investment becomes more attractive than stepwise investment when the latter entails a positive investment premium. This happens because greater uncertainty increases inertia and raises the incentive to avoid costly switches between stages, thereby promoting a lumpy investment strategy. By contrast, if a firm has discretion over capacity, then the stepwise investment strategy always dominates that of lumpy investment, as shown in Proposition 4. Intuitively, the flexibility to scale the capacity of the project offsets the reduction in the value of the stepwise investment strategy due to the cost that a firm must incur for the flexibility to proceed in stages. Additionally, as the right panel illustrates, the relative value of the two strategies is not only strictly greater than one, but shifts upwards as the investment cost becomes more convex, i.e., as  $\gamma$  increases. This implies that a more pronounced increase in the marginal cost of investment raises the incentive to adopt a stepwise investment strategy.



**Fig. 5** Relative value of the two investment strategies, i.e., lumpy and stepwise, versus  $\sigma$  under fixed capacity (left) and scalable capacity (right)

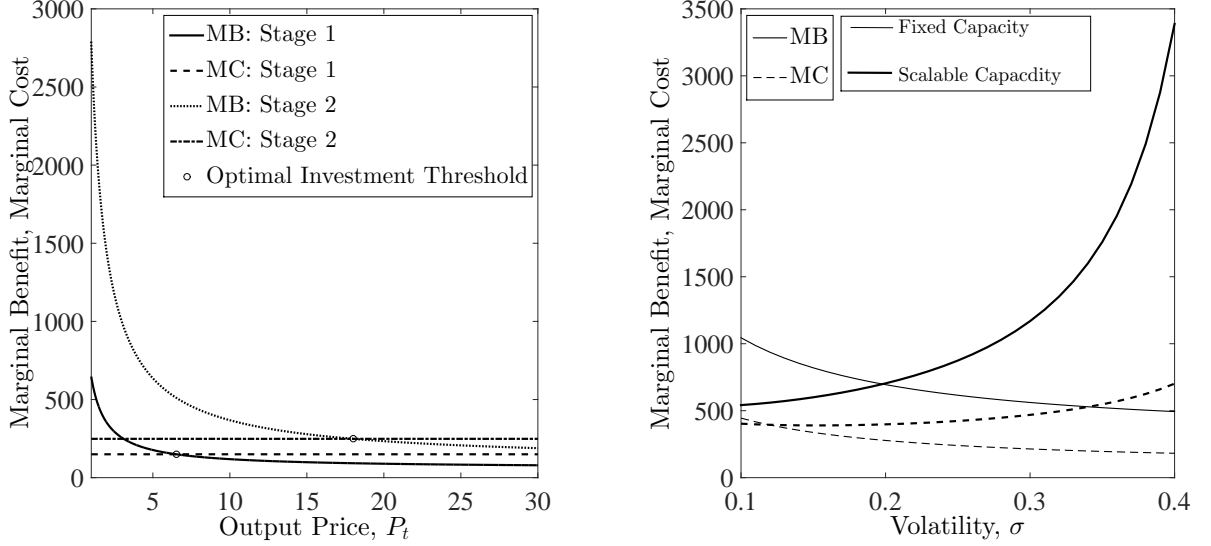
Figure 6 illustrates the impact of uncertainty on the excess capacity,  $\sum_i K_{s_i}^* - K_\ell^*$ , and the investment premium,  $\sum_i I(K_{s_i}^*) - I(K_\ell^*)$ , under stepwise investment for different values of  $a_j$ . As the left panel illustrates, greater uncertainty increases the wedge between the total capacity installed via stepwise and lumpy investment, while this result is more pronounced as the cost of the stepwise investment strategy increases. This happens because an increase in the investment premium raises the firm's incentive to increase the amount of installed capacity, and, thus, compensate for the extra cost associated with stepwise investment. As the right panel illustrates, the investment premium that is required in order to proceed in stages also increases with greater uncertainty. This is in contrast to Kort *et al.* [24], who show that if stepwise investment is associated with an investment premium, then greater uncertainty lowers a firm's willingness to proceed in stages by decreasing the investment premium for which a firm is indifferent between the two strategies. Since, in our model, the stepwise investment strategy always dominates, a direct comparison with Kort *et al.* [24] is not possible. Nevertheless, the right panel indicates that a firm is willing to incur an extra cost in order to proceed in stages so long as the cost of each modular project is less than that of lumpy investment, i.e., provided that condition (3) is satisfied.



**Fig. 6** Impact of  $\sigma$  on the excess capacity (left) and the investment premium (right)

The left panel in Figure 7 illustrates the MB and MC of delaying investment under scalable capacity for each stage of the project. Notice that for low price levels the MB exceeds the MC, and, as a result, the firm has an incentive to postpone investment. Furthermore, the MB decreases as the output price increases due to the effect of discounting, while the MC is constant. The right panel illustrates the impact of uncertainty on the total MB and MC of delaying investment in each stage of the project under fixed and scalable capacity. In the former case, the MB and MC decrease with greater uncertainty, while, in the latter case, the MB and MC increase, as shown in Proposition 6. Intuitively, the incentive to delay investment is greater when

the capacity of the project is scalable because a modular investment enables flexibility, thereby making it possible to adapt to uncertain market conditions.



**Fig. 7** MB and MC of delaying investment for stages  $i = 1, 2$  and  $\sigma = 0.2$  under scalable capacity (left) and total MB and MC under stepwise investment (right)

## 6 Concluding Remarks

Managerial flexibility is crucial for addressing the valuation and tradeoffs involved in capital projects, that are typically more complex than simple now-or-never investments. In this paper, we extend the results of Kort *et al.* [24] by assuming that a firm does not only have the flexibility to choose the investment strategy, in terms of lumpy versus stepwise investment, but also has discretion over both the investment timing and the size of the project. Thus, we determine not only the optimal investment threshold and the corresponding optimal capacity under lumpy and stepwise investment, but also the impact of price uncertainty on the relative value of the two investment strategies. Therefore, the contribution of this work is in delineating the interaction between various forms of managerial flexibility when a firm faces external pressures, e.g., market volatility.

While Kort *et al.* [24] show that, in the presence of an investment premium, the flexibility to proceed in stages becomes less valuable than lumpy investment with greater uncertainty, which is in contrast to the traditional real options intuition that emphasises the positive relationship between flexibility and uncertainty, implications from including different types of managerial flexibilities have not been examined thoroughly yet. We confirm the results of Kort *et al.* [24], however, in addition we show that, if a firm has discretion over capacity, then the stepwise investment strategy always dominates that of lumpy investment. This result emphasises that the relationship between flexibility and uncertainty requires further investigation. Indeed,

not only is the positive relationship between the value of flexibility and uncertainty case specific, but, more importantly, the impact of uncertainty on an isolated type of managerial discretion may be completely mitigated if the latter is combined with another type of flexibility. In this paper, we show that, although the flexibility to proceed in stages becomes less valuable than lumpy investment with greater uncertainty when a project has a fixed capacity, allowing for discretion over capacity mitigates this effect completely. More specifically, the reduction in the value of the stepwise investment strategy due to the cost that a firm incurs in order to have the flexibility to proceed in stages is completely offset by the extra value from the flexibility to scale the capacity of the project. Additionally, we show that the amount of installed capacity under stepwise investment is always greater than that under lumpy investment.

A limitation of this work is the exogenous price process, which implies that investment decisions do not affect future prices. This assumption can be relaxed by linking the output price with the amount of installed capacity via an inverse demand function. However, considering the results of Dangl [12], this is not expected to influence the main result of the paper. Nevertheless, it would still be interesting to investigate any quantitative difference due to the implications of installing a very large project. In order to obtain further insights on the robustness of the results regarding the relationship between uncertainty and various combinations of different types of flexibilities, we may also allow for production flexibility in the context of Hagspiel *et al.* [19], operational flexibility in the form of options to suspend and resume operations, or an alternative stochastic process, e.g., arithmetic Brownian motion or mean-reverting process. Additionally, the implications of irreversibility may be further analysed by introducing agency conflicts as in Löffler [28]. Finally, in line with Siddiqui and Takashima [35], this setup allows for exploration of game-theoretic considerations, e.g., how the presence of a rival impacts the decision to invest and the relative value of the two investment strategies under duopolistic competition.

## APPENDIX

**Proposition 1:** *The optimal investment threshold and the corresponding optimal capacity under lumpy and stepwise investment are:*

$$P_j^*(K_j^*) = \frac{I(K_j^*)}{K_j^*} \frac{\beta(\rho - \mu)}{\beta - 1} \quad \text{and} \quad K_j^* = \left[ \frac{a_j}{b} \frac{1}{\gamma(\beta - 1) - \beta} \right]^{\frac{1}{\gamma - 1}}, \quad \gamma(\beta - 1) - \beta > 0 \quad (\text{A-1})$$

**Proof:** By maximising the value of the now-or-never investment opportunity, we obtain the expression for the optimal capacity,  $\bar{K}_j^*$ , corresponding to the current output price  $P$ , as indicated in (A-2) for  $j = \ell, s_i$ .

$$\max_{\bar{K}_j} \bar{F}_j(P, \bar{K}_j) \Rightarrow \bar{K}_j^*(P) = \left[ \frac{1}{b\gamma} \left( \frac{P}{\rho - \mu} - a_j \right) \right]^{\frac{1}{\gamma - 1}} \quad (\text{A-2})$$

Next, the value of the option to invest is described in (A-3).

$$F_j(P) = \begin{cases} (1 - \rho dt) \mathbb{E}_P [F_j(P + dP)] & , P < P_j^* \\ \frac{PK_j^*}{\rho - \mu} - I(K_j^*) & , P \geq P_j^* \end{cases} \quad (\text{A-3})$$

By expanding the first branch on the right-hand side of (A-3) using Itô's lemma, we obtain the differential equation (A-4)

$$\frac{1}{2} \sigma^2 P^2 F_j''(P) + \mu P F_j'(P) - \rho F_j(P) = 0 \quad (\text{A-4})$$

which, for  $P < P_j^*$ , has the general solution that is indicated in (A-5).

$$F_j(P) = A_j P^\beta + B_j P^\delta \quad (\text{A-5})$$

Notice that  $\delta$  is the negative root of the quadratic  $\frac{1}{2} \sigma^2 x(x-1) + \mu x - \rho = 0$ , and, therefore,  $P \rightarrow 0 \Rightarrow B_j P^\delta \rightarrow \infty$ . Consequently, we must have  $B_j = 0$ , and, thus, we finally obtain (A-6).

$$F_j(P) = \begin{cases} A_j P^\beta & , P < P_j^* \\ \frac{PK_j^*}{\rho - \mu} - I(K_j^*) & , P \geq P_j^* \end{cases} \quad (\text{A-6})$$

By applying value-matching and smooth-pasting conditions between the two branches of (A-6) we obtain the expression for the endogenous constant and the optimal investment threshold, that are indicated in (A-7) and (A-8), respectively.

$$A_j = \frac{1}{P_j^{*\beta}} \left[ \frac{P_j^* K_j^*}{\rho - \mu} - I(K_j^*) \right] \quad (\text{A-7})$$

$$P_j^*(K_j^*) = \frac{I(K_j^*)}{K_j^*} \frac{\beta(\rho - \mu)}{\beta - 1} \quad (\text{A-8})$$

By inserting (A-8) into (A-2), we obtain the expression for the optimal capacity

$$K_j^* = \left[ \frac{a_j}{b} \frac{1}{\gamma(\beta - 1) - \beta} \right]^{\frac{1}{\gamma - 1}}, \quad \gamma(\beta - 1) - \beta > 0 \quad (\text{A-9})$$

while the final expression for the optimal investment threshold is obtained by inserting (A-9) into (A-8) and is indicated in (A-10).

$$P_j^*(K_j^*) = \frac{a_j \beta(\rho - \mu)(\gamma - 1)}{\gamma(\beta - 1) - \beta} \quad (\text{A-10})$$

□

**Proposition 2:**  $P_{s_1}^*$  is independent of  $P_{s_2}^*$ .

**Proof:** If we assume that  $\tau_{s_2} \geq \tau_{s_1}$ , then  $P_{s_1}^* \leq P_{s_2}^*$  and the maximised option value in the case of staged investment is indicated in (A-11).

$$F_s(P) = \left( \frac{P}{P_{s_1}^*} \right)^\beta \left[ \frac{P_{s_1}^* K_{s_1}^*}{\rho - \mu} - I(K_{s_1}^*) + \left( \frac{P_{s_1}^*}{P_{s_2}^*} \right)^\beta \left[ \frac{P_{s_2}^* K_{s_2}^*}{\rho - \mu} - I(K_{s_2}^*) \right] \right] \quad (\text{A-11})$$

Hence,  $p_{s_1}$  satisfies the first-order necessary condition (A-12)

$$\beta \left( -\frac{1}{P_{s_1}^*} \right) \left[ \frac{P_{s_1}^* K_{s_1}^*}{\rho - \mu} - I(K_{s_1}^*) \right] + \frac{K_{s_1}^*}{\rho - \mu} = 0 \quad (\text{A-12})$$

from which we have:

$$P_{s_1}^* = \frac{I(K_{s_1}^*)}{K_{s_1}^*} \frac{\beta(\rho - \mu)}{\beta - 1} \quad (\text{A-13})$$

Consequently,  $P_{s_1}^*$  is independent of  $P_{s_2}^*$ , i.e., the presence of the second stage does not affect the decision to invest in the first one. Note that the assumption  $P_{s_1}^* < P_{s_2}^*$  can be expressed as in (A-14).

$$\frac{I(K_{s_1}^*)}{I(K_{s_2}^*)} < \frac{K_{s_1}^*}{K_{s_2}^*} \quad (\text{A-14})$$

□

**Proposition 3:**  $\frac{\partial K_j^*}{\partial \sigma} > 0$  and  $\frac{\partial P_j^*}{\partial \sigma} > 0$ .

**Proof:** By differentiating the expression of the optimal capacity in (A-9) we have:

$$\frac{\partial K_j^*}{\partial \sigma} = K_j^* \left[ \frac{-\frac{\partial}{\partial \sigma} \beta}{\gamma(\beta - 1) - \beta} \right], \quad \gamma(\beta - 1) - \beta > 0 \quad (\text{A-15})$$

Since  $\frac{\partial}{\partial \sigma} \beta < 0$ , we have  $\frac{\partial K_j^*}{\partial \sigma} > 0$ . Additionally, the expression of the optimal investment threshold is:

$$\begin{aligned} P_j^*(K_j^*) &= \frac{I(K_j^*)}{K_j^*} \frac{\beta(\rho - \mu)}{\beta - 1} \\ &= \frac{a_j K_j^* + b K_j^{*\gamma}}{K_j^*} \frac{\beta(\rho - \mu)}{\beta - 1} \\ &= \left( a_j + b K_j^{*\gamma-1} \right) \frac{\beta(\rho - \mu)}{\beta - 1} \end{aligned} \quad (\text{A-16})$$

Since  $\frac{\partial}{\partial \sigma} \frac{\beta}{\beta - 1} > 0$  and  $\frac{\partial}{\partial \sigma} K_j^* > 0$  we have  $\frac{\partial}{\partial \sigma} P_j^* > 0$ . □

**Proposition 4:** *If a firm has discretion over capacity, then  $F_s(P) > F_\ell(P)$ .*

**Proof:** The relative value of the two strategies is indicated in (A-17).

$$\frac{F_s(P)}{F_\ell(P)} = \sum_i \frac{F_{s_i}(P)}{F_\ell(P)} \quad (\text{A-17})$$

In order to show that  $F_s(P) > F_\ell(P)$ , we will show that each term on the right-hand side of (A-17) is greater than one, i.e:

$$\frac{F_{s_i}(P)}{F_\ell(P)} = \frac{\left(\frac{P}{P^*}\right)^\beta \left[ \frac{P^* K_{s_i}^*}{\rho - \mu} - I(K_{s_i}^*) \right]}{\left(\frac{P}{P_\ell^*}\right)^\beta \left[ \frac{P_\ell^* K_\ell^*}{\rho - \mu} - I(K_\ell^*) \right]} = \left(\frac{K_{s_i}^*}{K_\ell^*}\right)^\beta \frac{I(K_\ell^*)^{\beta-1}}{I(K_{s_i}^*)^{\beta-1}} > 1, i = 1, 2 \quad (\text{A-18})$$

By manipulating the expression of the relative value in (A-18) we obtain (A-19)

$$\left(\frac{K_{s_i}^*}{K_\ell^*}\right)^\beta \frac{I(K_\ell^*)^{\beta-1}}{I(K_{s_i}^*)^{\beta-1}} > 1 \Leftrightarrow \frac{\frac{I(K_\ell^*)^{\beta-1}}{K_\ell^{*\beta}}}{\frac{I(K_{s_i}^*)^{\beta-1}}{K_{s_i}^{*\beta}}} > 1 \Leftrightarrow \frac{K_{s_i}^*}{K_\ell^*} \frac{\frac{I(K_\ell^*)^{\beta-1}}{K_\ell^{*\beta-1}}}{\frac{I(K_{s_i}^*)^{\beta-1}}{K_{s_i}^{*\beta-1}}} > 1 \quad (\text{A-19})$$

where the expression for  $\frac{K_{s_i}^*}{K_\ell^*}$  is indicated in (A-20).

$$\frac{K_{s_i}^*}{K_\ell^*} = \frac{\left[ \frac{a_{s_i}}{b} \frac{1}{\gamma(\beta-1)-\beta} \right]^{\frac{1}{\gamma-1}}}{\left[ \frac{a_\ell}{b} \frac{1}{\gamma(\beta-1)-\beta} \right]^{\frac{1}{\gamma-1}}} = \left( \frac{a_{s_i}}{a_\ell} \right)^{\frac{1}{\gamma-1}} \quad (\text{A-20})$$

By substituting the expression for  $\frac{K_{s_i}^*}{K_\ell^*}$  into (A-19) and by inserting the expression for the optimal capacity from (A-9) into (A-19), we finally obtain (A-21).

$$\frac{K_{s_i}^*}{K_\ell^*} \frac{\frac{I(K_\ell^*)^{\beta-1}}{K_\ell^{*\beta-1}}}{\frac{I(K_{s_i}^*)^{\beta-1}}{K_{s_i}^{*\beta-1}}} = \left( \frac{a_{s_i}}{a_\ell} \right)^{\frac{1}{\gamma-1}} \left( \frac{a_\ell}{a_{s_i}} \right)^{\beta-1} = \left( \frac{a_\ell}{a_{s_i}} \right)^{\beta - \frac{\gamma}{\gamma-1}} \quad (\text{A-21})$$

Notice that  $(\beta - 1)(\gamma - 1) > 1 \Leftrightarrow \beta > \frac{\gamma}{\gamma-1}$ , which is the required condition so that  $K_j^* \in \mathbb{R}^+$ . Additionally, by differentiating (A-18) with respect to  $\sigma$  as in (A-22), we can determine the relationship between uncertainty and the relative value of the two strategies.

$$\frac{\partial}{\partial \sigma} \frac{F_{s_i}(P)}{F_\ell(P)} = \frac{\partial}{\partial \sigma} \left( \frac{a_\ell}{a_{s_i}} \right)^{\beta - \frac{\gamma}{\gamma-1}} = \left( \frac{a_\ell}{a_{s_i}} \right)^{\beta - \frac{\gamma}{\gamma-1}} \ln \left( \frac{a_\ell}{a_{s_i}} \right) \frac{\partial \beta}{\partial \sigma} \quad (\text{A-22})$$



Notice that if  $a_{s_i} < a_\ell$ , then greater uncertainty decreases the relative value of the stepwise investment strategy. Consequently, if  $a_{s_i} < a_\ell \forall i \in \mathbb{N}$ , then  $\sigma \nearrow \Rightarrow \frac{F_s(P)}{F_\ell(P)} \searrow$ . In addition, from (A-21) we conclude that the stepwise investment strategy is always more valuable than lumpy investment.

$$\frac{F_s(P)}{F_\ell(P)} = \sum_i \frac{F_{s_i}(P)}{F_\ell(P)} = \sum_i \left( \frac{a_\ell}{a_{s_i}} \right)^{\beta - \frac{\gamma}{\gamma-1}} > 1, \text{ if } a_{s_i} < a_\ell, \forall i \in \mathbb{N} \quad (\text{A-23})$$

□

**Proposition 5:**  $K_\ell^* < \sum_{i=1}^n K_{s_i}^* \Leftrightarrow a_\ell^{\frac{1}{\gamma-1}} < \sum_{i=1}^n a_{s_i}^{\frac{1}{\gamma-1}}$ .

**Proof:** The optimal capacity of the project under lumpy and stepwise investment is described in (A-24).

$$K_j^* = \left[ \frac{a_j}{b} \frac{1}{\gamma(\beta-1)-\beta} \right]^{\frac{1}{\gamma-1}} \quad (\text{A-24})$$

From (A-24) we have  $K_\ell^* < K_{s_1}^* + K_{s_2}^* \Leftrightarrow a_\ell^{\frac{1}{\gamma-1}} < a_{s_1}^{\frac{1}{\gamma-1}} + a_{s_2}^{\frac{1}{\gamma-1}}$ . Notice that this inequality cannot be solved analytically for all values of  $\gamma$ . However, since  $\gamma > \frac{\beta}{\beta-1} > 1$ , it is easy to see that  $\gamma = 2 \Rightarrow a_\ell < a_{s_1} + a_{s_2}$ , which holds by assumption. Similarly, by substituting the expression for  $K_j^*$  into (3), we find that the assumption  $I(K_\ell^*) < \sum_i I(K_{s_i}^*)$  is equivalent to (A-25).

$$a_\ell^{\frac{\gamma}{\gamma-1}} < a_{s_1}^{\frac{\gamma}{\gamma-1}} + a_{s_2}^{\frac{\gamma}{\gamma-1}} \quad (\text{A-25})$$

Consequently, it is not sufficient to assume that  $a_\ell < a_{s_1} + a_{s_2}$  in order to ensure that, at the optimal solution, the modular project is more expensive than the lumpy one. Instead, this assumption depends on a more complex relationship between the cost parameters  $a_j$  and the convexity of the cost function. □

**Corollary 1:** *The MB is steeper than the MC.*

**Proof:** The result follows from differentiating the MB and MC of delaying investment with respect to the output price. Notice that the MC is positive and independent of the output price, while  $\frac{\partial}{\partial P} MB < 0$ . □

**Proposition 6:** *If  $K_j$  is fixed, then  $\frac{\partial}{\partial \sigma} MB < 0$ ,  $\frac{\partial}{\partial \sigma} MC < 0$ , and  $|\frac{\partial}{\partial \sigma} MB| < |\frac{\partial}{\partial \sigma} MC|$ , whereas if  $K_j$  is scalable, then  $\frac{\partial}{\partial \sigma} MB > 0$ ,  $\frac{\partial}{\partial \sigma} MC > 0$ , and  $\frac{\partial}{\partial \sigma} MB > \frac{\partial}{\partial \sigma} MC$ .*

**Proof:** The MB and MC of delaying investment is indicated in (A-26).

$$MB = MC \Leftrightarrow \frac{\beta I(K_j^*)}{P_j^*} + \frac{K_j^*}{\rho - \mu} = \frac{\beta K_j^*}{\rho - \mu} \quad (\text{A-26})$$

Notice that if the capacity of the project is fixed, i.e., i.e.,  $K_j^* \equiv K_j$ , then an increase in  $\sigma$  lowers both the MB and the MC as indicated in (A-27).

$$\frac{\partial MB}{\partial \sigma} = \frac{I(K_j) \frac{\partial}{\partial \sigma} \beta}{P_j^*} < 0 \quad \text{and} \quad \frac{\partial MC}{\partial \sigma} = \frac{K_j \frac{\partial}{\partial \sigma} \beta}{\rho - \mu} < 0 \quad (\text{A-27})$$

However, from (A-13) we know that  $\frac{I(K_j)}{P_j^*} < \frac{K_j}{\rho - \mu}$ , and, therefore, the MC of delaying investment decreases by more than the MB.

$$\left| \frac{\partial MC}{\partial \sigma} \right| > \left| \frac{\partial MB}{\partial \sigma} \right| \quad (\text{A-28})$$

By contrast, if the capacity of the project is scalable, then the MB and MC of delaying investment increase with greater price uncertainty. Indeed, for  $P < P_j^*$  we have:

$$\frac{\partial MB}{\partial \sigma} = \frac{I(K_j^*) \frac{\partial}{\partial \sigma} \beta + \beta \frac{\partial}{\partial \sigma} I(K_j^*)}{p_j} + \frac{\frac{\partial}{\partial \sigma} K_j^*}{\rho - \mu} > 0 \quad (\text{A-29})$$

The second term on the right-hand side of (A-29) is positive since  $\frac{\partial}{\partial \sigma} K_j^* > 0$ . Notice also that, even though  $\frac{\partial}{\partial \sigma} \beta < 0$ ,  $\beta$  is bounded from below since  $\beta > 1$ . By contrast, since the capacity of the project is not bounded and  $\frac{\partial}{\partial \sigma} I(K_j^*) > 0$ , the decrease in  $\beta$  is mitigated by the increase in the investment cost. The impact of  $\sigma$  on the MC is indicated in (A-30).

$$\frac{\partial MC}{\partial \sigma} = \frac{K_j^* \frac{\partial}{\partial \sigma} \beta + \beta \frac{\partial}{\partial \sigma} K_j^*}{\rho - \mu} \quad (\text{A-30})$$

Notice that the reduction in  $\beta$  makes the impact of  $\sigma$  on  $K_j^*$  less pronounced, and, therefore, the second term on the right-hand side of (A-29) is greater than right-hand side of (A-30). Since the first term on the right-hand side of (A-29) is positive, we have:

$$\frac{\partial MB}{\partial \sigma} > \frac{\partial MC}{\partial \sigma} \quad (\text{A-31})$$

Finally, notice that the second term on the left-hand side of (A-26) is constant when the capacity is fixed and increasing when the capacity is scalable. Similarly, the reduction of the first term due to the decrease in  $\beta$  with greater uncertainty is offset by the increase in  $K_j^*$ . Consequently, the impact of  $\sigma$  on the MB of delaying investment is not only reversed when the firm has discretion over capacity but it is also more pronounced.  $\square$

## References

1. Abel AB, Eberly JC (1996) Optimal Investment with Costly Reversibility. *The Review of Economic Studies* 63(4): 581–593.

2. Adkins R, Paxson D (2015) Stepwise Investment Value under Stage Specific Parameters. working paper, Bradford University School of Management, Bradford, UK.
3. Alvarez L, Stenbacka R (2004) Optimal Risk Adoption: A Real Options Approach. *Economic Theory* 23: 123–147.
4. Anand KS, Girotra K (2007) The Strategic Perils of Delayed Differentiation. *Management Science* 53(5): 697–712.
5. Arrow K, Fisher AC (1974) Environmental Preservation, Uncertainty, and Irreversibility Quarterly. *Journal of Economics* 88: 312–319.
6. Baldursson F, Karatzas I (1997) Irreversible Investment and Industry Equilibrium. *Finance and Stochastics* 1: 69–89.
7. Baldwin CY, Clark KB (2000) Design Rules: The Power of Modularity. MIT Press, Cambridge, MA.
8. Boomsma TK, Meade N, Fleten SE (2012) Renewable Energy Investments under Different Support Schemes: A Real Options Approach. *European Journal of Operational Research* 220(1): 225–237.
9. Bøckman T, Fleten SE, Juliussen E, Langhammer HJ, Revdal I (2008) Investment Timing and Optimal Capacity Choice for Small Hydropower Projects. *European Journal of Operational Research* 109(1): 255–267.
10. Chod J, Rudi N (2005) Resource Flexibility with Responsive Pricing. *Operations Research* 53 (3): 532–548.
11. Chronopoulos M, De Reyck B, Siddiqui AS (2012) The Value of Capacity Sizing Under Risk Aversion and Operational Flexibility. *IEEE Transactions on Engineering Management* 60(2): 272–288.
12. Dangel T (1999) Investment and Capacity Choice under Uncertain Demand. *European Journal of Operational Research* 117: 415–428.
13. Dixit AK, Pindyck RS (1994) Investment under Uncertainty. Princeton University Press, Princeton, NJ, USA.
14. Doege J, Schiltknecht P, Lüthi HJ (2006) Risk Management of Power Portfolios and Valuation of Flexibility. *OR Spectrum* 28(2): 267–287.
15. Gahungu J, Smeers Y (2012) A Real Options Model for Electricity Capacity Expansion. Université Catholique de Louvain, CORE, B-1348, Louvain-la-Neuve, Belgium.
16. Gamba A, Fusari N (2009) Valuing Modularity as a Real Option. *Management Science* 55(11): 1877–1896.
17. Gollier C, Proult D, Thais F, Walgenwitz G (2005) Choice of Nuclear Power Investments under Price Uncertainty: Valuing Modularity. *Energy Economics* 27: 667–685.
18. Goyal M, Netessine S (2007) Strategic Technology Choice and Capacity Investment under Demand Uncertainty. *Management Science* 53 (2): 192–207.
19. Hagspiel V, Huisman K, Kort P (2014) Production Flexibility and Capacity Investment under Demand Uncertainty. working paper, Tilburg University, Tilburg, The Netherlands.
20. He H, Pindyck RS (1992) Investments in Flexible Production Capacity. *Journal of Economic Dynamics and Control* 16: 575–599.
21. Henry C (1974) Investment Decisions under Uncertainty: The Irreversibility Effect. *American Economic Review* 64: 89–104.
22. Huisman KJM, Kort PM (2015) Strategic Capacity Investment under Uncertainty. *RAND Journal of Economics* 46(2): 376–408.
23. Jørgensen S, Kort PM (1993) Optimal Dynamic Investment Policies under Concave–Convex Adjustment Costs. *Journal of Economic Dynamics and Control* 17: 153–180.
24. Kort PM, Murto P, Pawlina G (2010) Uncertainty and Stepwise Investment. *European Journal of Operational Research* 202(1): 196–203.
25. Leahy JV (1993) Investment in Competitive Equilibrium: The Optimality of Myopic behavior. *Quarterly Journal of Economics* 108(4): 1105–1133.
26. Longstaff FA, Schwartz ES (2001) Valuing American Options by Simulation: A Simple Least–Squares Approach. *Review of Financial Studies* 14(1): 113–147.
27. Lund, D (2005), “How to Analyse the Investment–Uncertainty Relationship in Real Option Models,” *Review of Financial Economics* 14: 311–322

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28. Löffler, C, T Pfeiffer, and G Schneider (2013), "The Irreversibility Effect and Agency Conflicts," *Theory and Decision* 74: 219–239.
  29. Mackintosh J (2003) Ford Learns to Bend with the Wind. *Financial Times*, 14 February.
  30. Majd S, Pindyck RS (1987) Time to Build, Option Value, and Investment Decisions. *Journal of Financial Economics* 18: 7–27.
  31. Malchow-Møller N, Thorsen BJ (2005) Repeated Real Options: Optimal Investment behavior and a Good Rule of Thumb. *Journal of Economic Dynamics & Control* 29: 1025–1041.
  32. Pawlina G, Kort PM (2003) Strategic Capital Budgeting: Asset Replacement under Market Uncertainty. *OR Spectrum*, 25(4): 443–479.
  33. Pindyck RS (1988) Irreversible Investment, Capacity Choice, and the Value of the Firm. *American Economic Review* 79: 969–985.
  34. Rodrigues A, Armada MJ (2007) The Valuation of Modular Projects: A Real Options Approach to the Value of Splitting. *Global Finance Journal* 18: 205–227.
  35. Siddiqui AS, Takashima R (2012) Capacity Switching Options under Rivalry and Uncertainty. *European Journal of Operational Research* 222(3): 583–595.
  36. Siddiqui AS, KM Maribu (2009) Investment and Upgrade in Distributed Generation under Uncertainty. *Energy Economics* 31(1): 25–37.
  37. Takashima R, Siddiqui AS, Nakada S (2012) Investment Timing, Capacity Sizing, and Technology Choice of Power Plants. *Handbook of Networks in Power Systems I Energy Systems* 303–321.